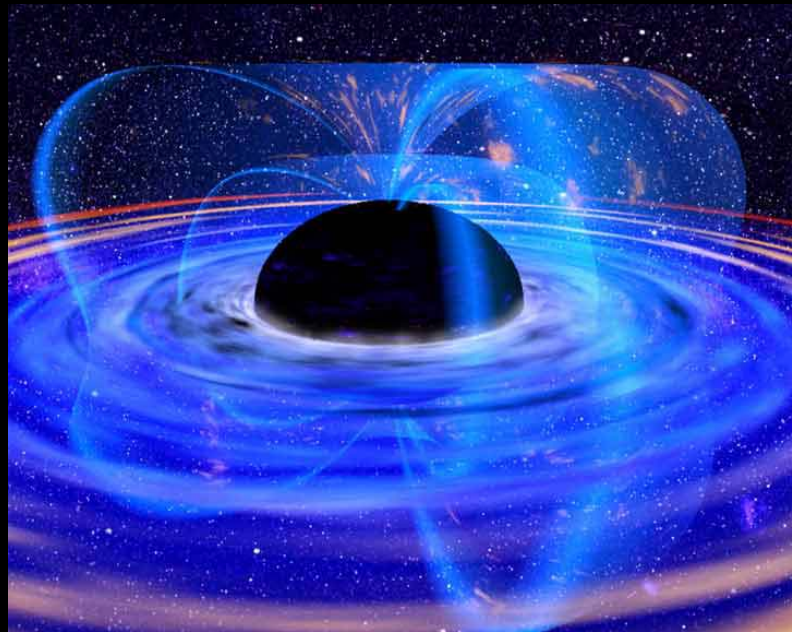


XMM Observations of MCG-6-30-15

Christopher Stephen Reynolds
(UMD-Astronomy)



Credits

- Project PI : Joern Wilms
- US lead: Chris Reynolds
- Also
 - ◆ Mitchell Begelman
 - ◆ James Reeves
 - ◆ Silvano Molendi
 - ◆ Ruediger Staubert
 - ◆ Eckhard Kendziorra

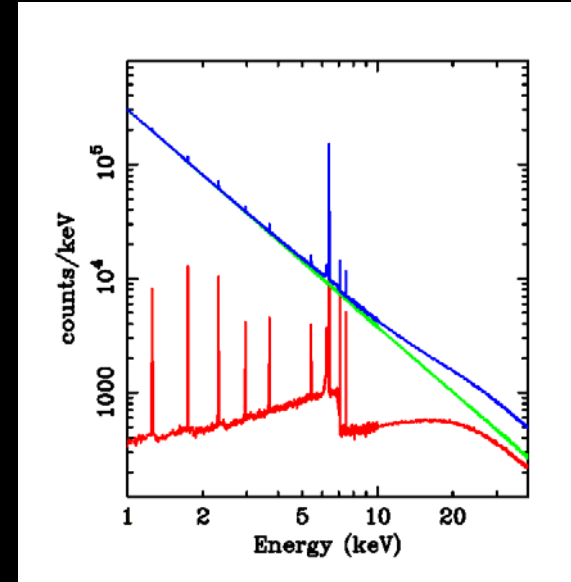
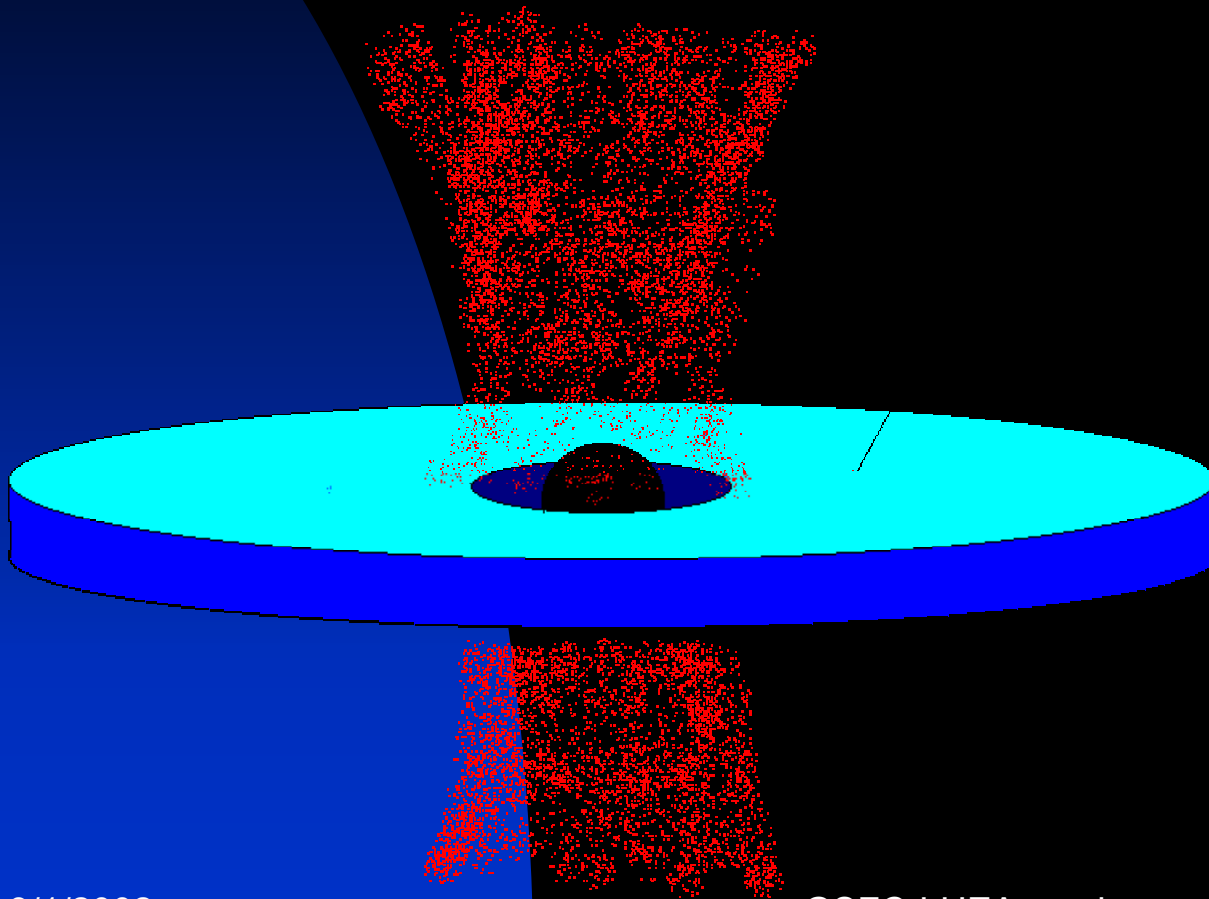
Outline

- Biography of MCG-6-30-15
- Our XMM observations
- Evidence for BH spin extraction
- Spin extraction mechanisms
- Open questions

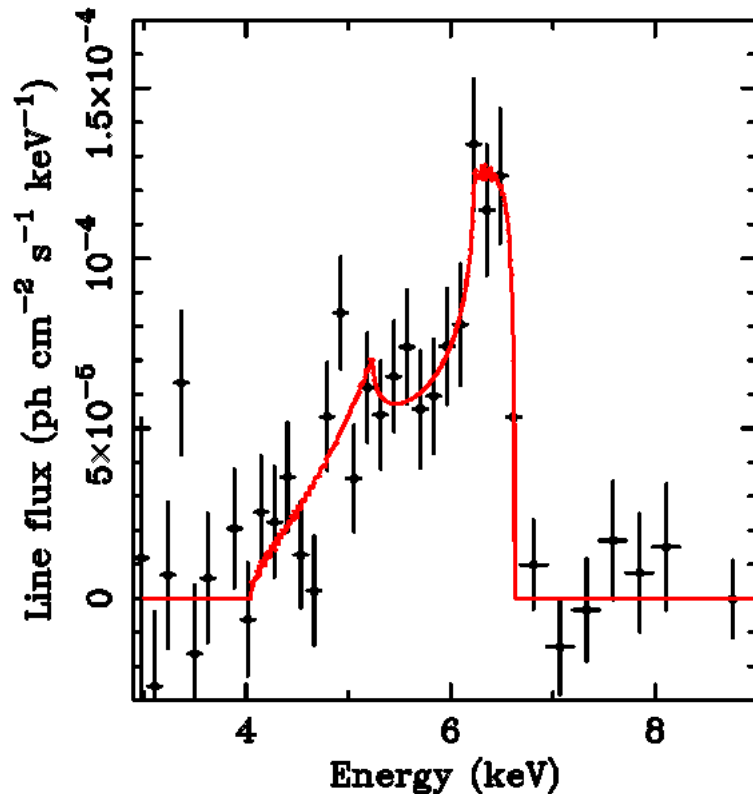
Intro to MCG-6-30-15

- Unremarkable S0 galaxy in Centaurus ($z=0.008$)
- Hosts Seyfert 1.2 nucleus
- Favourite AGN for x-ray study
 - ◆ Bright ($\text{few} \times 10^{-11} \text{ erg/s/cm}^2$)
 - ◆ Rapidly variable
- Become test-bed for X-ray studies of relativistic accretion disks

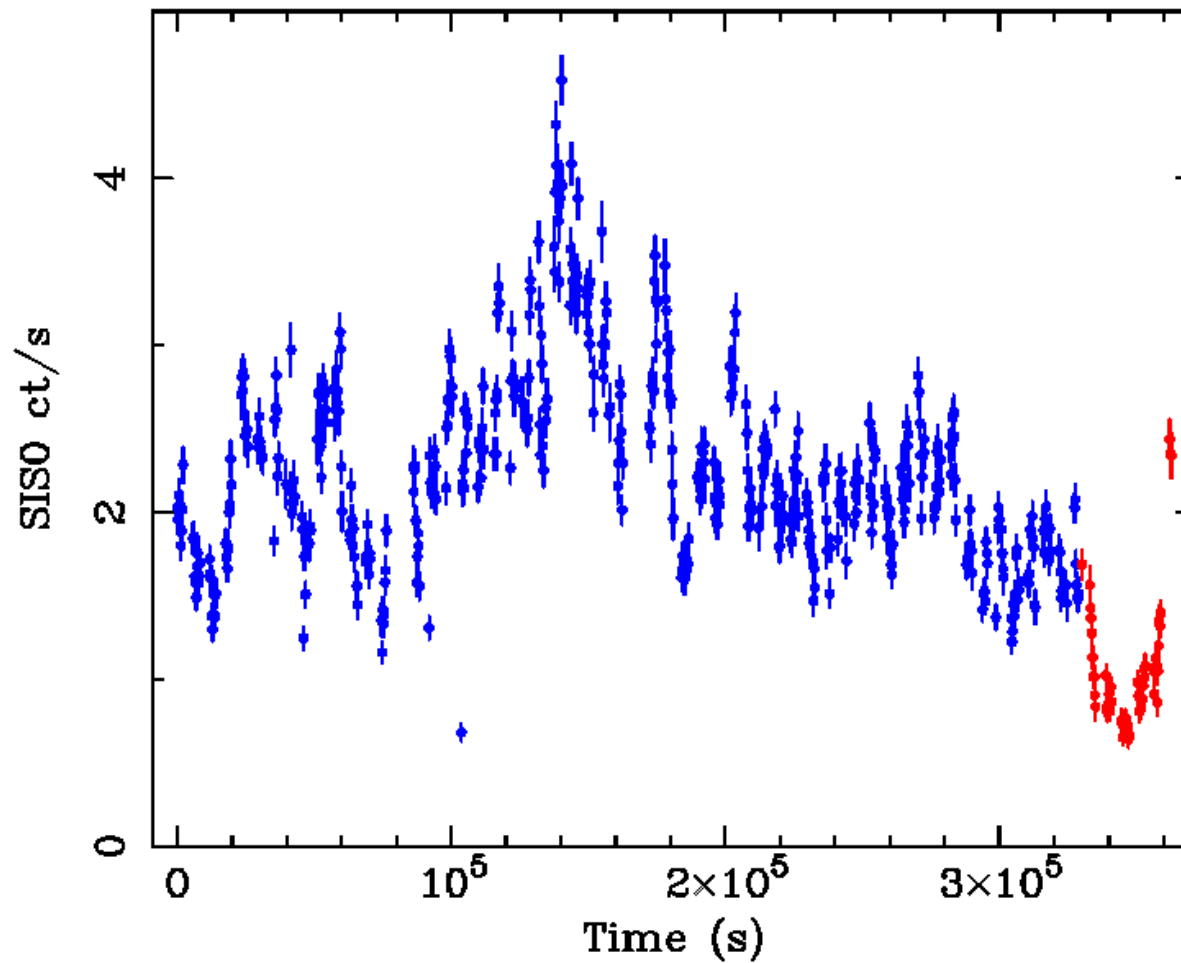
X-ray reflection...



... and accretion disks

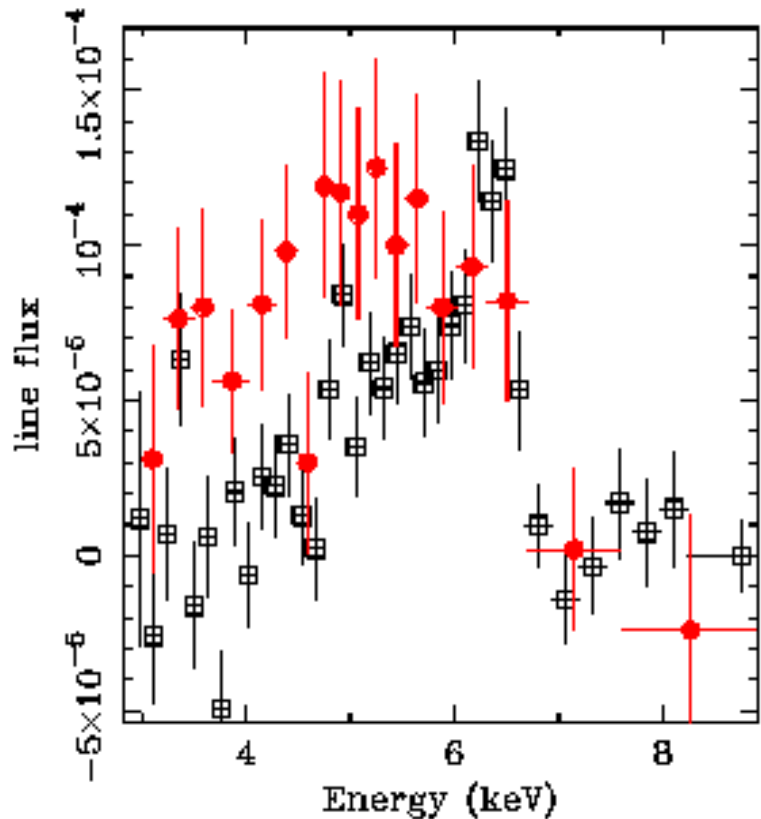


- Doppler shifts and gravitational redshifts broaden and skew line
 - ◆ First seen in MCG-6-30-15 (Tanaka et al. 1995)
 - ◆ Generic feature in Seyfert 1 nuclei (Nandra et al. 1997)

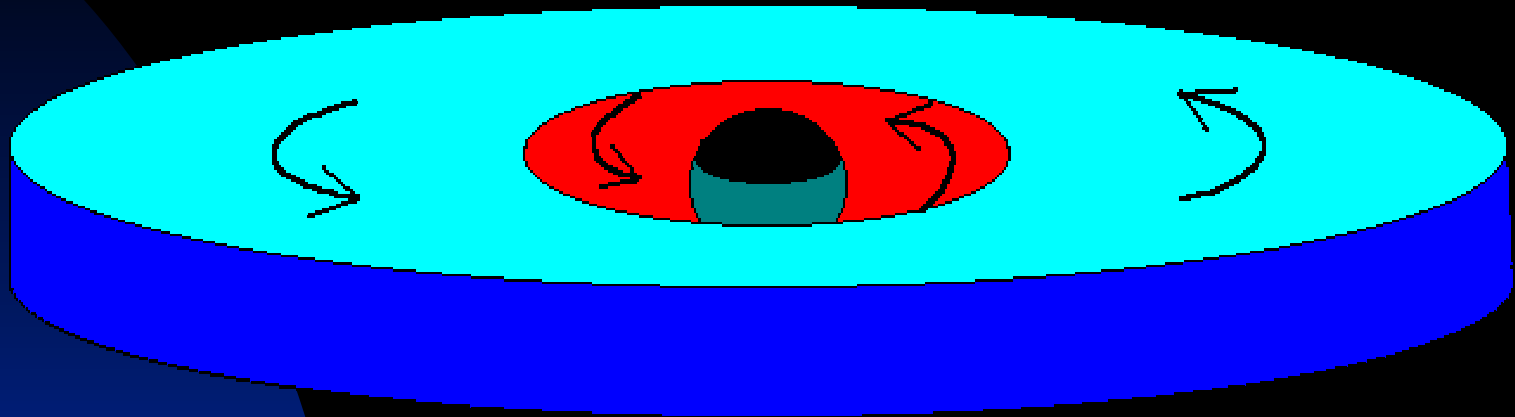


Iwasawa et al. (1996)

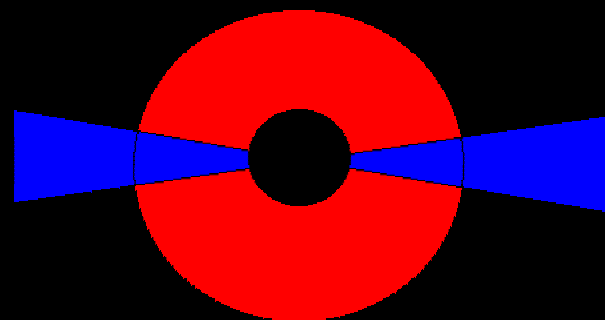
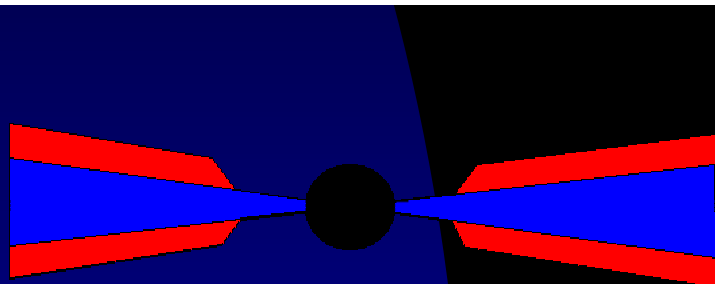
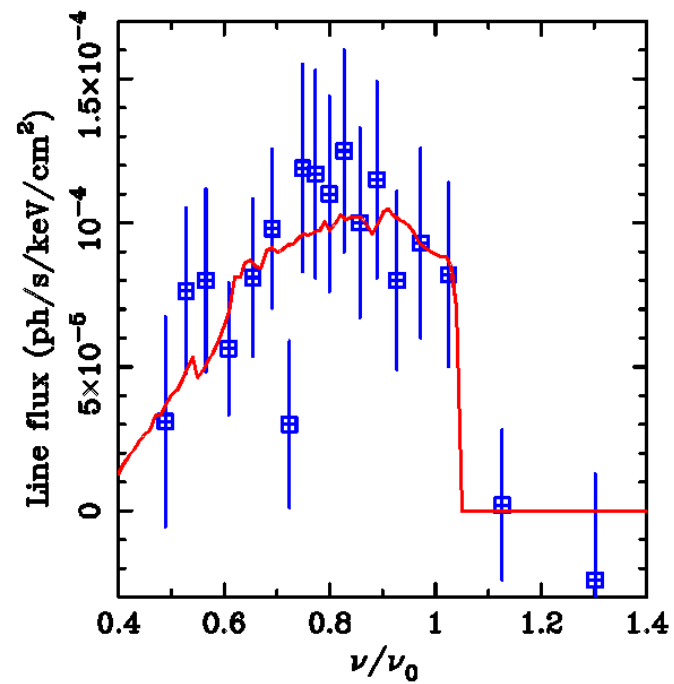
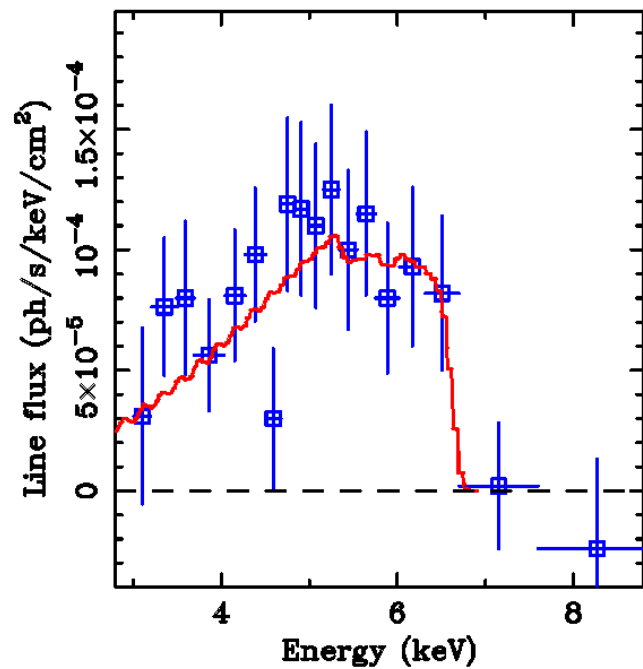
Black hole spin?



- “Deep minimum” state found in ASCA data on MCG-6-30-15
 - ◆ Flux drops by factor 2
 - ◆ Line becomes broader
 - ◆ Line becomes stronger
- Need line emission from inside of $6GM/c^2$
- Implies spinning hole?



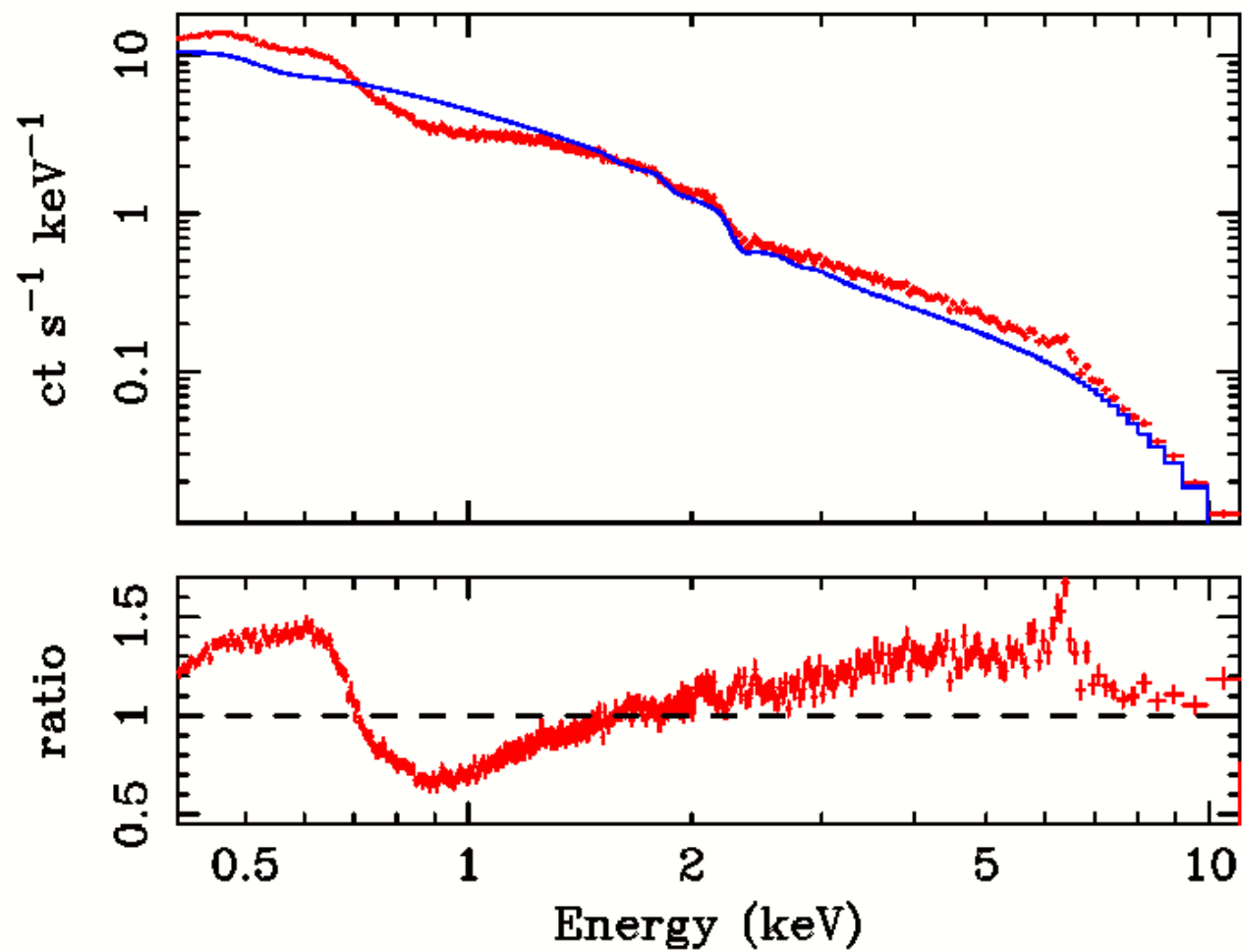
- Radius of marginal stability
- Outside – Keplerian accretion disk, slow inflow
- Inside – material rapidly plunges into hole



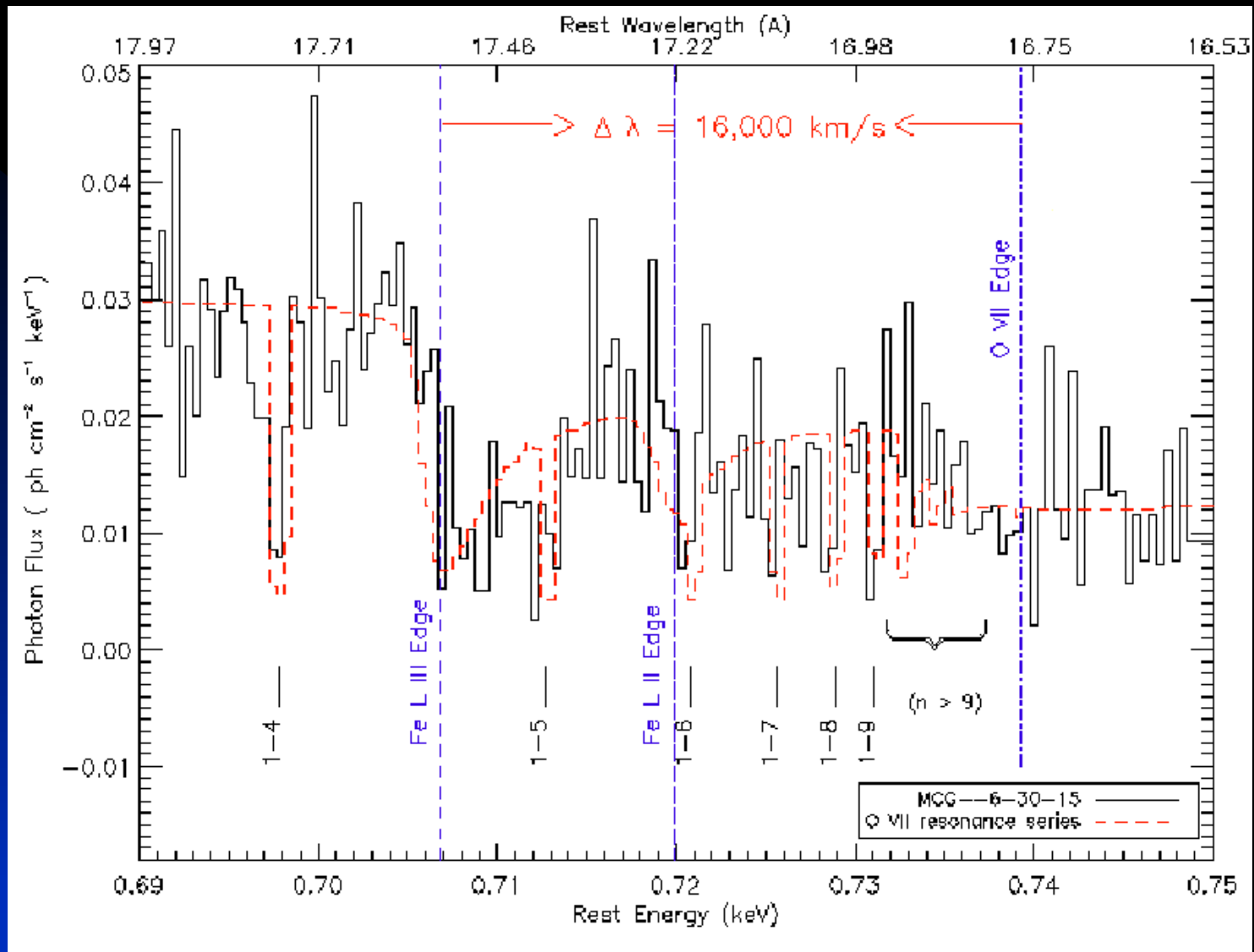
Our XMM observation

- 100ks observation of MCG-6-30-15
- Caught object in “deep minimum”
- In this talk, will present
 - ◆ EPIC-PN data
 - ◆ (MOS slightly piled-up, but agrees)
 - ◆ Time-averaged spectrum
- Still need to look at detailed variability

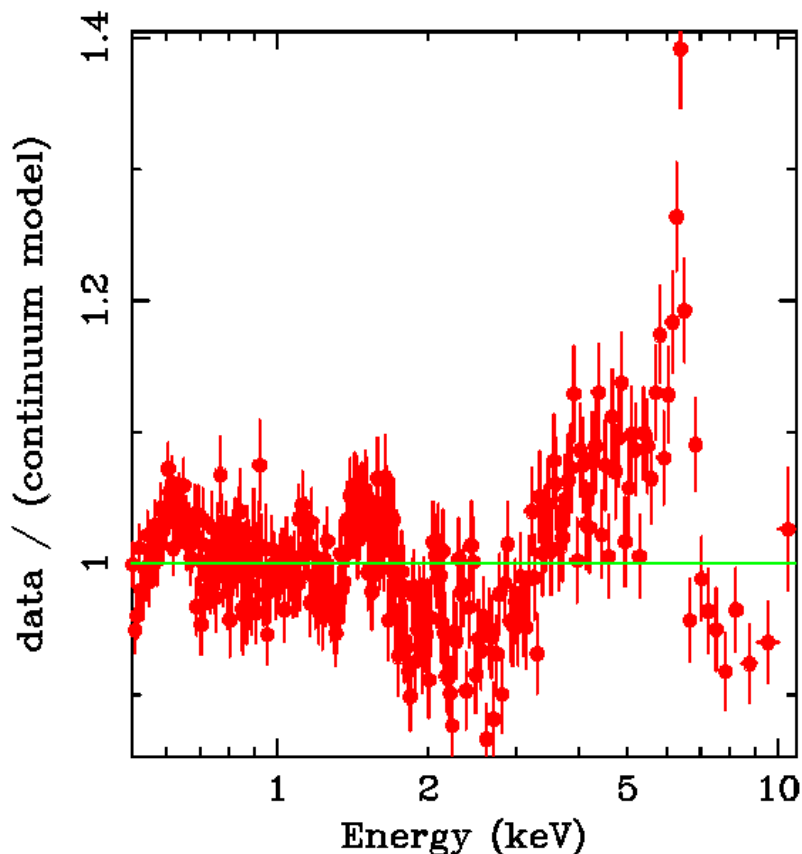




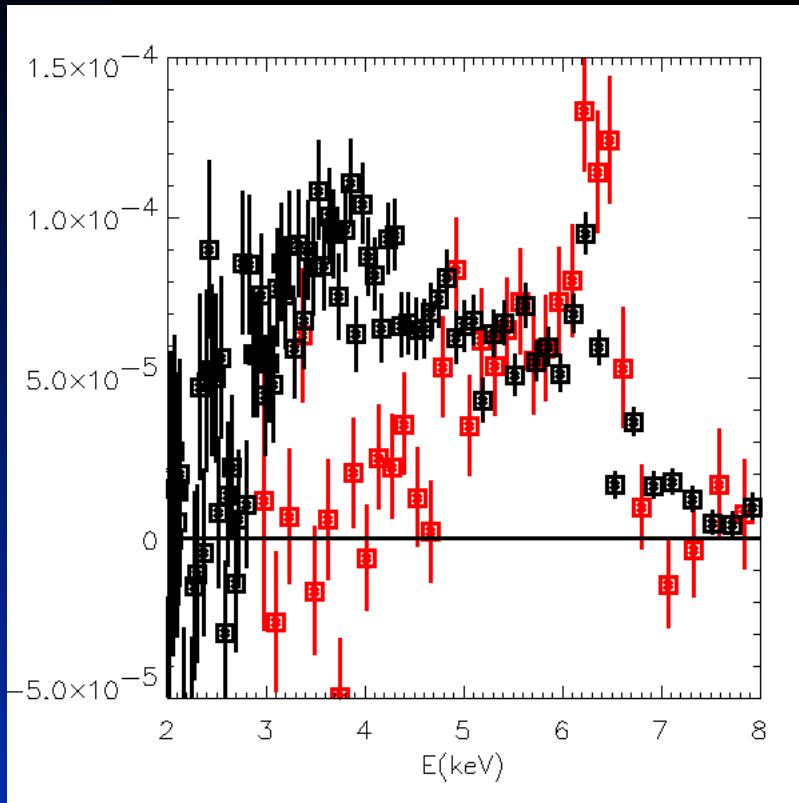




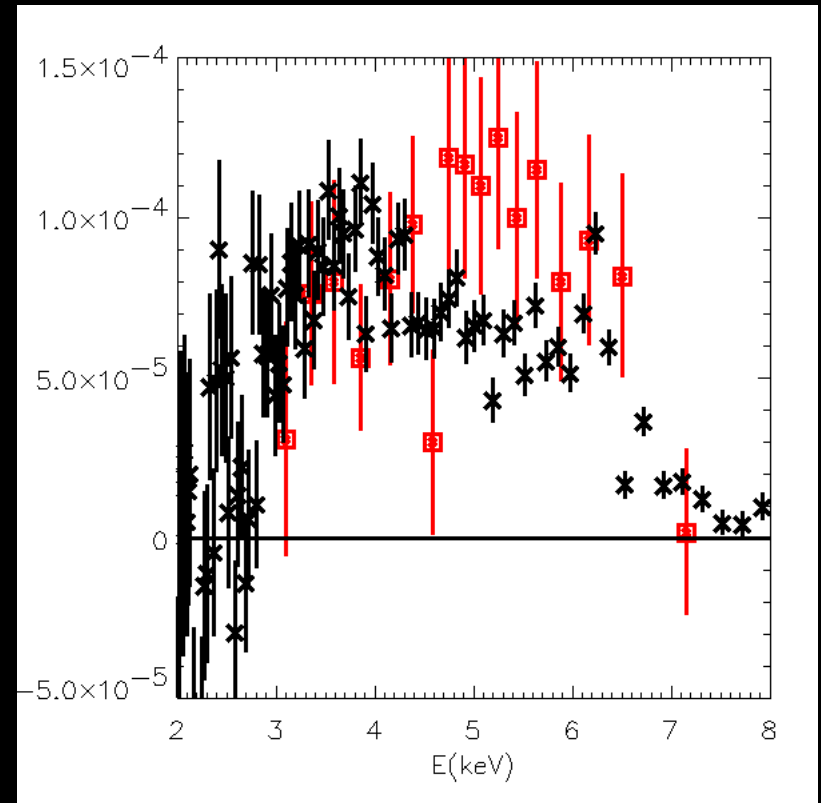
Lee et al. (2001)



- Construct empirical WA model (including line emission)
- Isolate spectral features from disk
- First cut – make a “fluxed line” profile
- Compare with ASCA...



Compared to time-averaged
line profile from ASCA

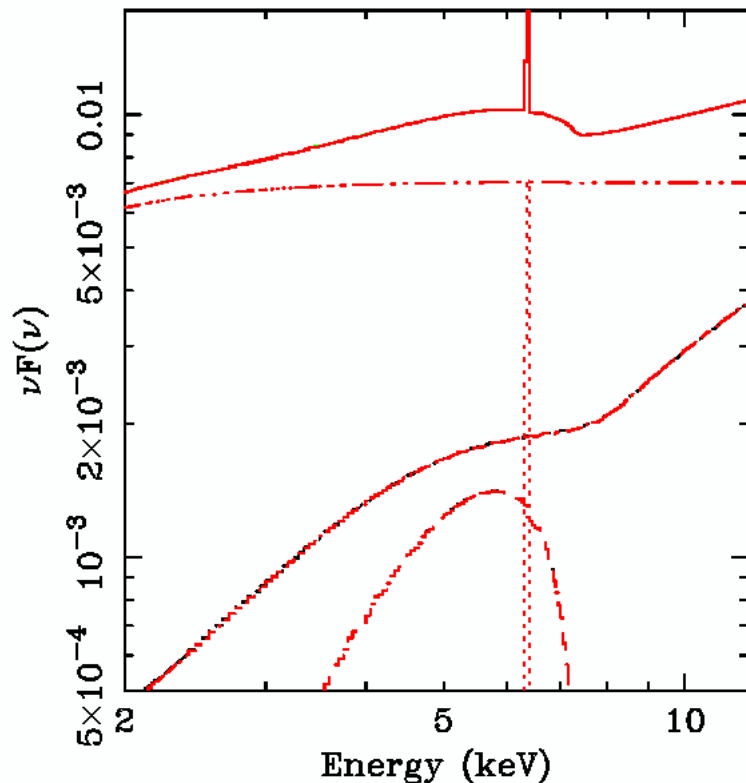


Compared to “deep minimum”
line profile from ASCA

Detailed spectral models

- Powerlaw (Comptonized) continuum
- Warm absorption (empirical RGS fit)
- Reflection from ionized disk (Magdziarz & Zdziarski 1995)
- Iron fluorescence
- Weak recombination line emission
- Relativistic smearing applied to lines AND reflection continuum

Basic result



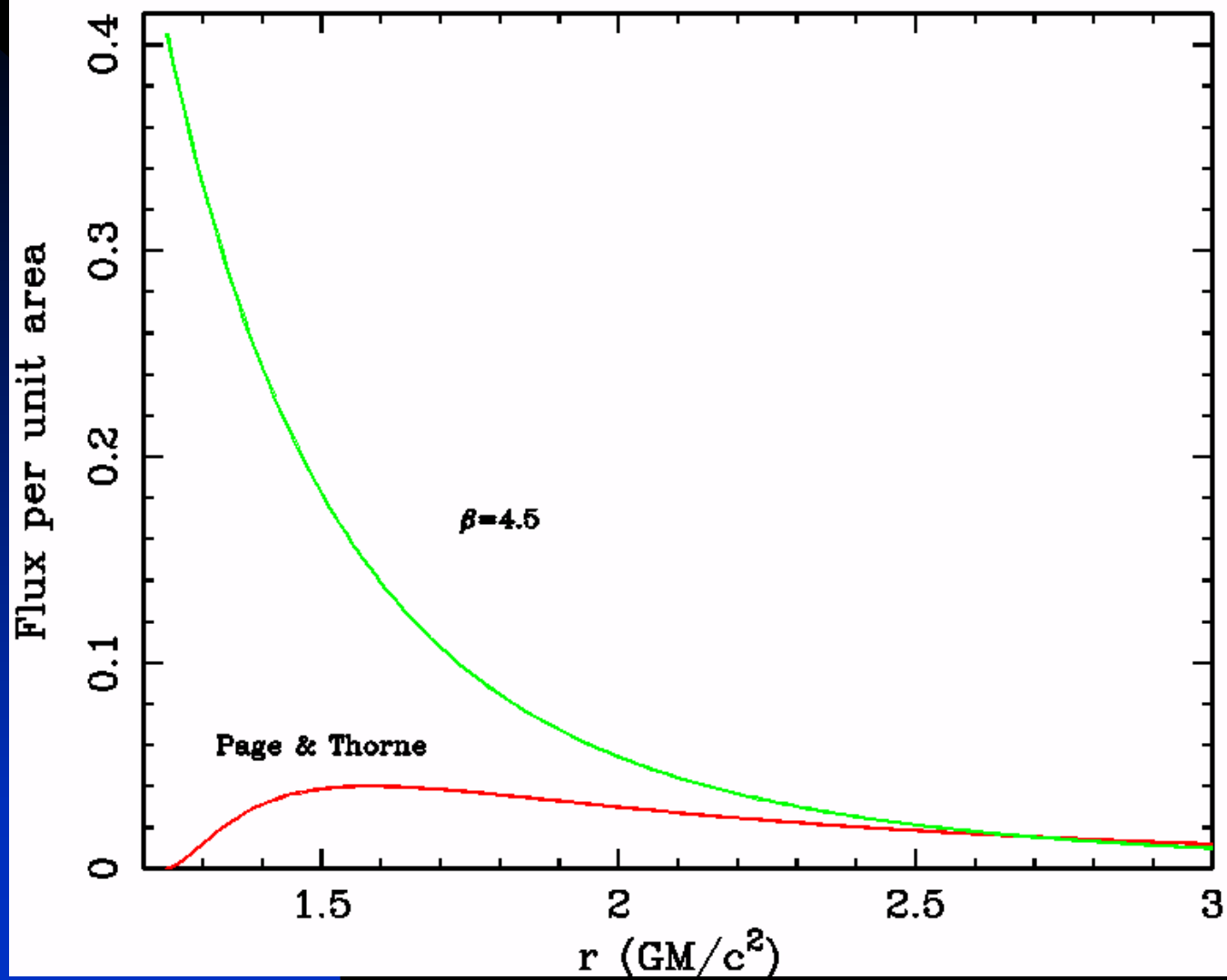
- Require extreme degree of broadening!
- Implies very centrally concentrated X-ray source
- $F(r) \sim r^{-\beta}$, $4.5 < \beta < 6.0$
- $R_{\text{in}} < 2.0 \text{ GM}/c^2$

Robustness

- General result robust to
 - ◆ Calibration issues (seen in MOS)
 - ◆ Reasonable continuum curvature
 - ◆ Assumed inclination
 - ◆ Compton broadening of the line

The trouble with “pure” accretion disks

- Standard disk model
 - ◆ Page, Novikov, Thorne
 - ◆ Thin, radiatively-efficient, α -model
 - ◆ Zero-torque boundary at RMS
 - ◆ Radiated power zero at RMS, peaks, then tends to r^{-3}
- Not concentrated enough to explain these data!



Black Hole Spin Extraction Hypothesis

- Black hole spin is only other source of energy in the system
- Hypothesis
 - ◆ Inner accretion disk is torqued by the black hole spin – mechanical work is done on inner disk
 - ◆ Result is a very centrally concentrated energy source

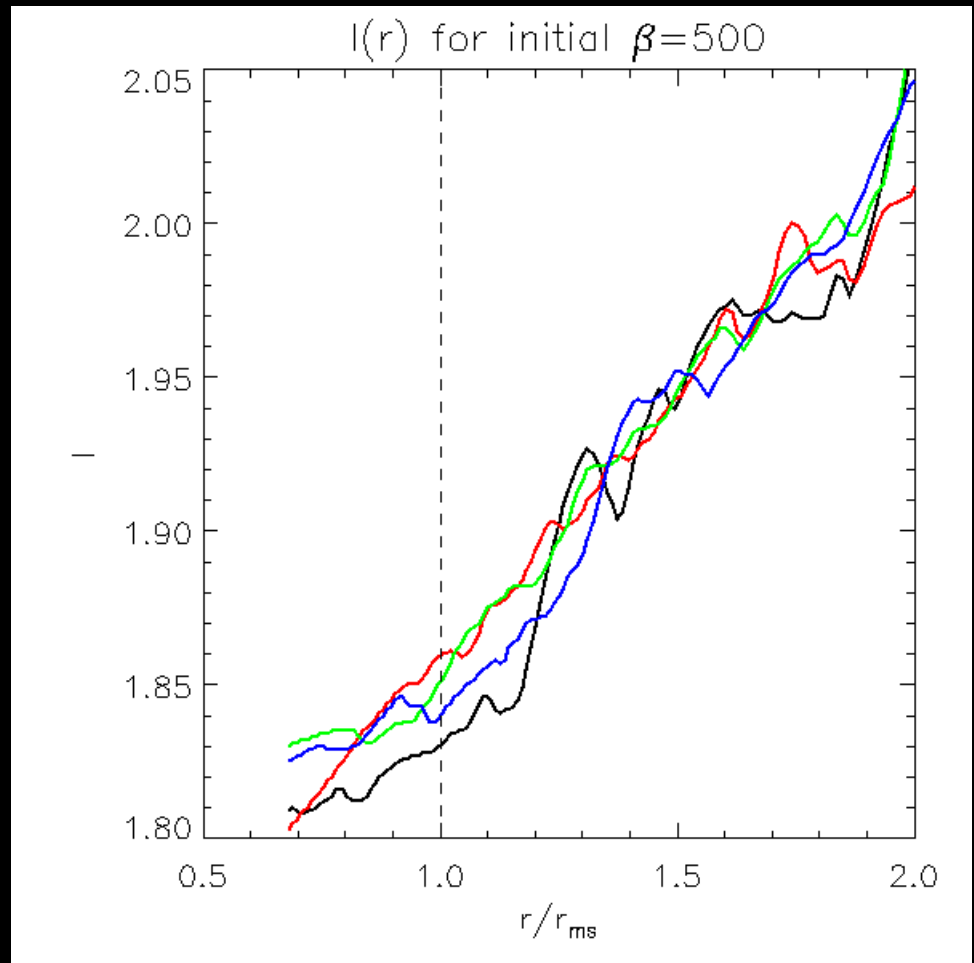
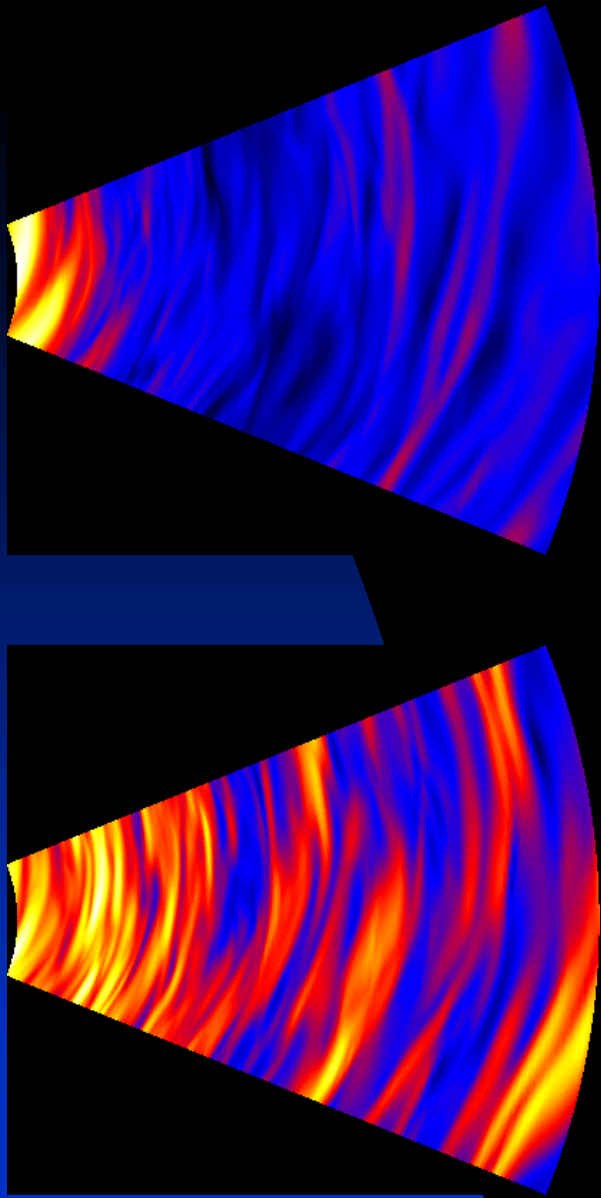
I : Spin extraction via the plunging region

- Gammie (1999), Krolik (1999), Agol & Krolik (2000)
- Suppose magnetic fields couple plunging region to rest of disk
 - ◆ Can place inner part of accretion flow onto negative-energy “counter-rotating” orbits
 - ◆ Accretion diminishes black hole energy – energy extracted from BH
 - ◆ “Penrose effect” (Penrose 1969)

- Numerical MHD simulations
 - ◆ Hawley (2000), Krolik & Hawley (2001), Armitage, Reynolds & Chiang (2001)
 - ◆ Non-relativistic simulations in Pseudo-Newtonian potential

$$\Phi = -\frac{GM}{r - r_{Sch}}$$

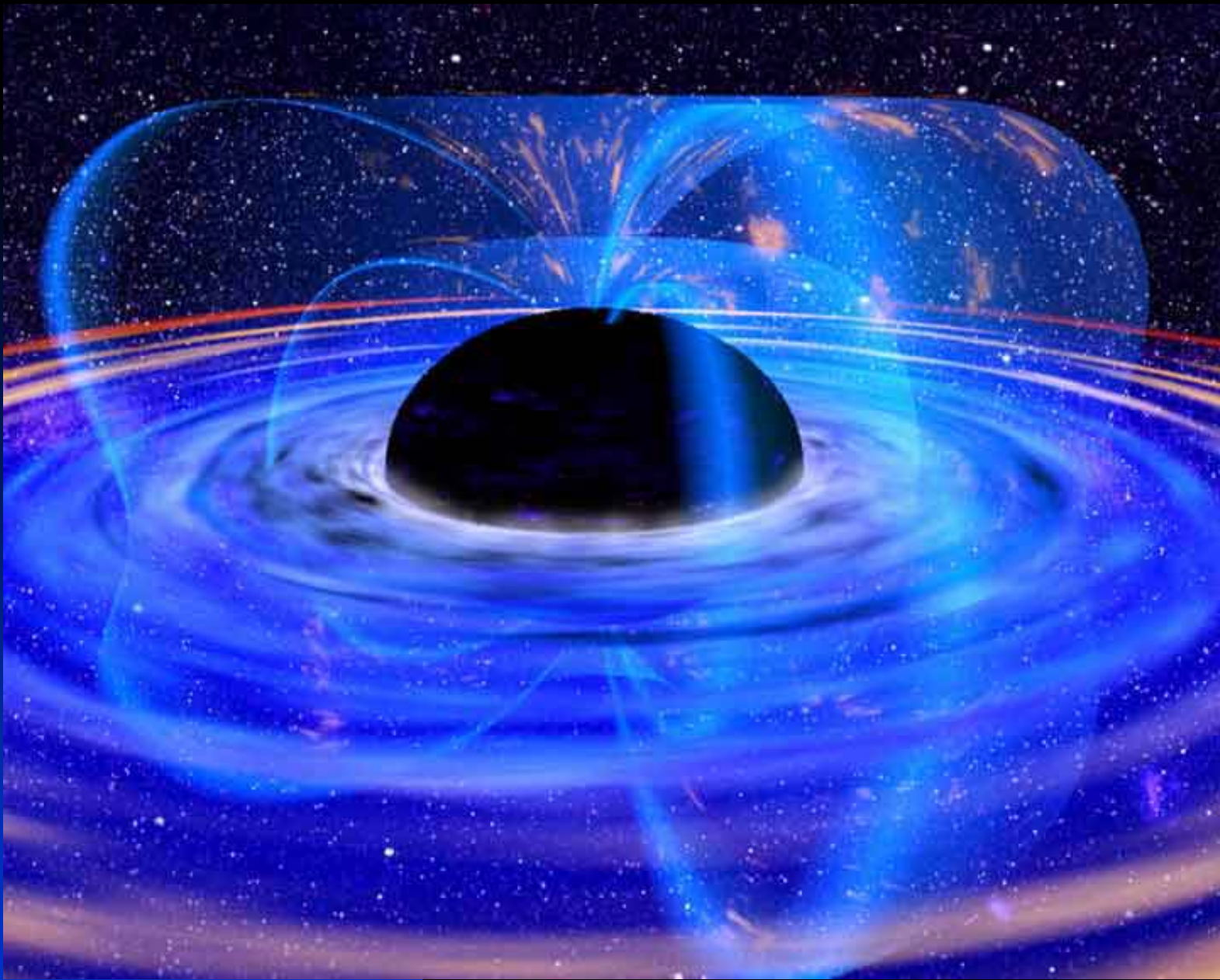
- ◆ Support possibility of magnetic couple between plunging region and disk



Reynolds & Armitage (2001)

II : Spin extraction by direct coupling to BH

- Blandford-Znajek (1977)
 - ◆ Externally imposed magnetic field will lead to extraction of spin energy from BH
 - ◆ “Virtual” Penrose effect
- Magnetic field linking BH to disk
 - ◆ Extracted energy deposited in disk
 - ◆ Will then be radiated (after accounting for viscous transport)



NASA/
Dana Berry

Open questions

- Nature of variability?
- Scenario I
 - ◆ Spin-component always present
 - ◆ Disk fades during “deep minimum” for unspecified reasons
- Scenario II
 - ◆ Trade-off between spin-component and disk-component
 - ◆ Sporadic torquing of inner disk accompanied by halting of accretion flow

- Radio-loud/radio-quiet dichotomy
 - ◆ MCG-6-30-15 is radio quiet, but seems to possess rapidly spinning BH
 - ◆ What other factors are relevant for RL/RQ dichotomy?
 - ◆ Need more XMM data on variety of RL and RQ objects...
- The nature of the black hole magnetosphere
 - ◆ What is strength and configuration of field threading BH?
 - ◆ Do magnetic instabilities give rise to some of the variability?
 - ◆ What is the governing physics?

Conclusions

- New XMM data for MCG-6-30-15 find very broad disk reprocessing features
- Hypothesize that the inner accretion disk is being torqued by the black hole spin
 - ◆ Directly via BZ mechanism
 - ◆ Indirectly via plunging region
- Open issues
 - ◆ Counter-example to simple spin-hypothesis for RL/RQ dichotomy
 - ◆ What is nature of “deep minimum”?